Exploitation of X-band Synthetic Aperture Radars for rainfall retrieval within GPM

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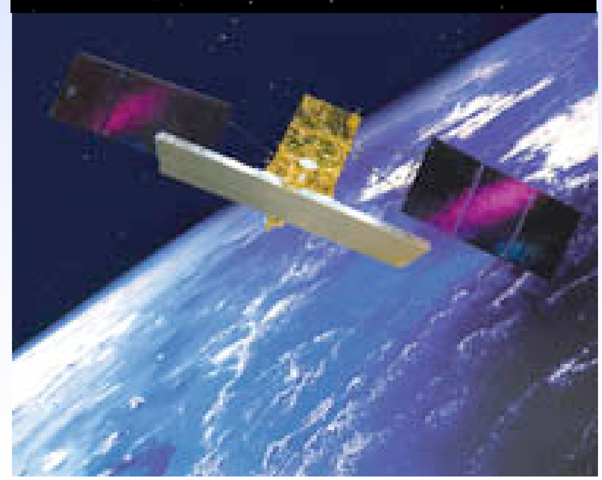
MOTIVATION

- **GPM CONCEPT**
  - **Getting precipitation data from an ensemble of satellite microwave sensors, both passive and active, has recently renovated the issue of using** Synthetic Aperture Radars at X band (X-SARs)**.**
    - The SAR frequency at **X band** (9.6 GHz) is not too far from **Ku band** (14 GHz) and rainfall signatures have been already revealed by **previous X-SARs measurements** (e.g. SAR-X SIR-C in 1994).
    - The **high spatial resolution** (~100 m) of SAR sensors might provide new insights into the structure of precipitating clouds form space.
    - Unlike the **Precipitation Radar**, which provides highly resolved vertical precipitation **profiles, SAR measure the** slant-path integrated scattering and attenuation of precipitation.
    - **Near-future SAR satellites** will also measure the **co-polar and cross-polar polarized backscattering,** produced by precipitation along the slant path
- **SCIENTIFIC BENEFITS**
  - The measurement of **highly-resolved precipitation** over land **where microwave radiometers have had limited success.**
    - X-SAR precipitation retrievals will be especially valuable **over mountainous terrain** (where ground based radars are obstructed), but also **over ocean** with different problems to be solved.
  - Contribution to **GPM constellation resources**

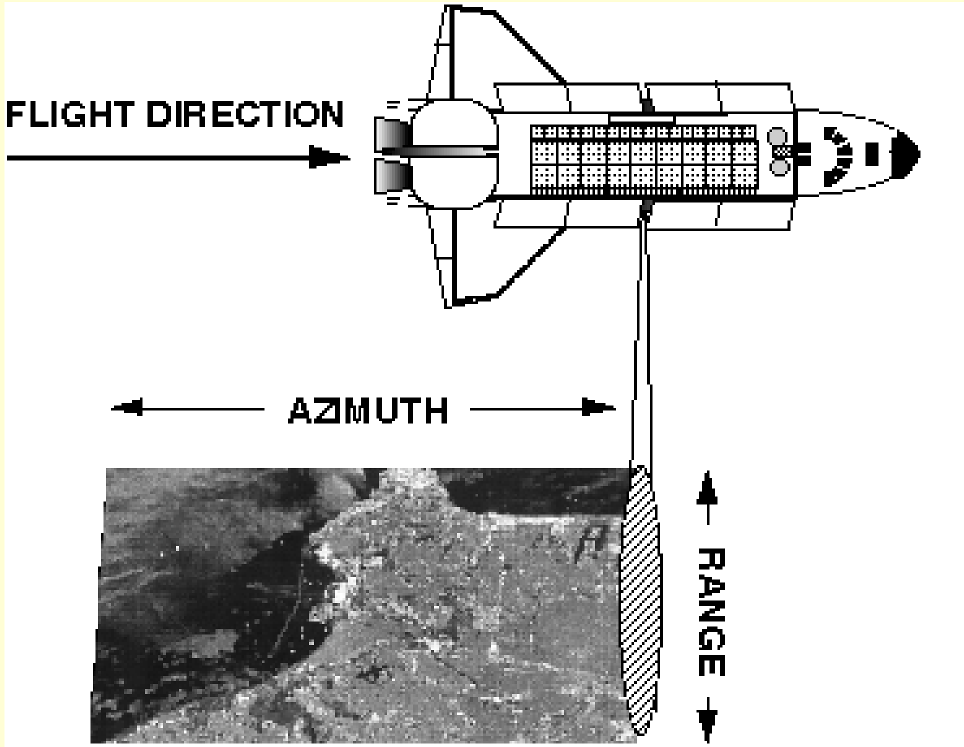
INTERNATIONAL CONTEXT

- The **use of X-SAR data** in the near future can take advantage of the satellite missions already planned by some **European space agencies**.
  - The **TerraSAR-X (TSX)** will be launched by the Deutsches Zentrum f. Luft u. Raumfahrt (DLR) in 2007
  - the **Constellation of 4+2 Small Satellites for Mediterranean basin Observations (COSMO-SkyMed)** will be launched by the Agenzia Spaziale Italiana (ASI) in 2007-08
    - **X-band + hyperspectral camera** on 2 other satellites
    - **Stripmap mode** (res.: 3-15 m, scene: 40x40 km^2)
    - **Multi-polarimetric mode** (HH, VV, HV select, res.: 15 m, scene: 30x30 km^2)
    - **ScanSAR mode** (res.: 30-100 m, scene: 200x200 km^2)

COSMO SkyMed satellite system

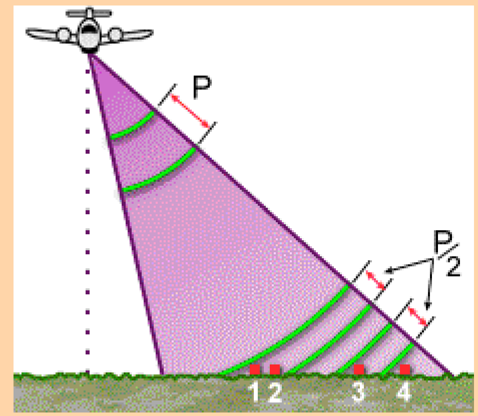


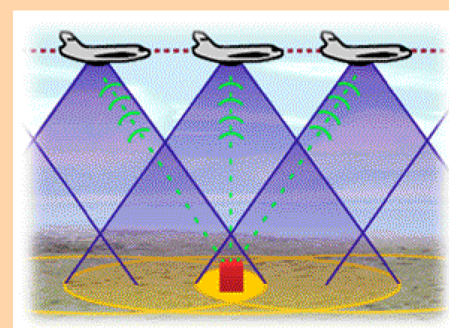
SAR PROCESSING AND GEOMETRY



- **Ground range resolution (cross-track)**
  ⇒ **Chirp bandwidth B and off-nadir angle θ**

  $\Delta x = [c/2B]/\sin\theta$



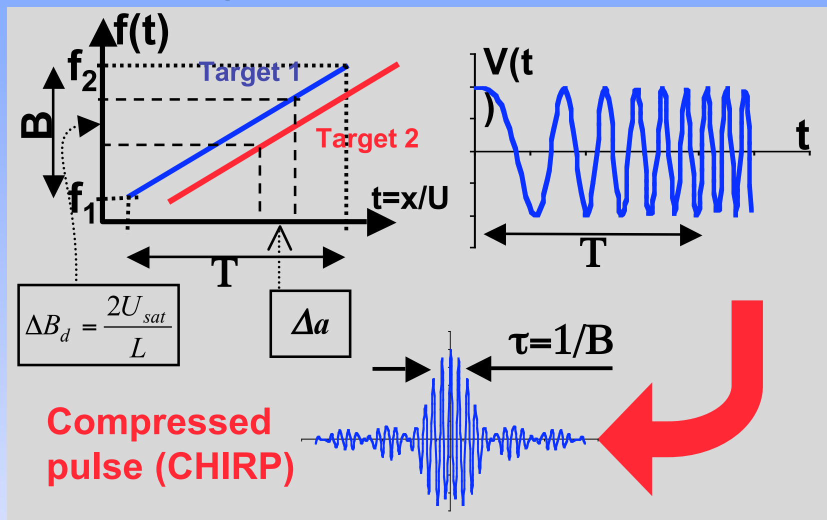


- **Azimuth resolution (along-track)**
  ⇒ **synthetic aperture lenght or Doppler beam sharpening**

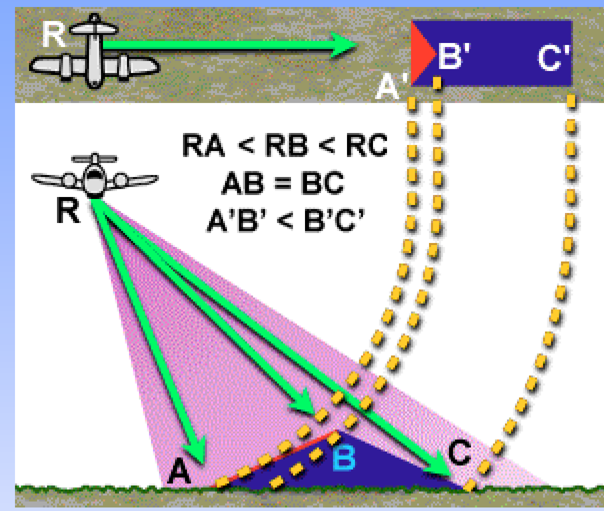
  $\Delta a = N_{look} \cdot L_{ant}/2$

SOME ISSUES ON SAR DATA PROCESSING

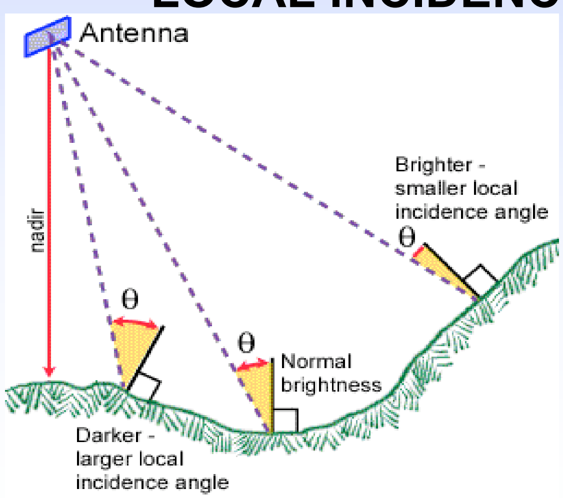
DOPPLER BANDWIDTH



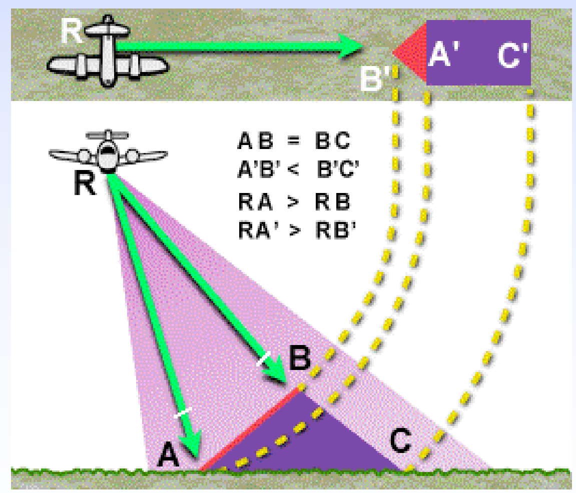
FORE-SHORTENING



LOCAL INCIDENCE

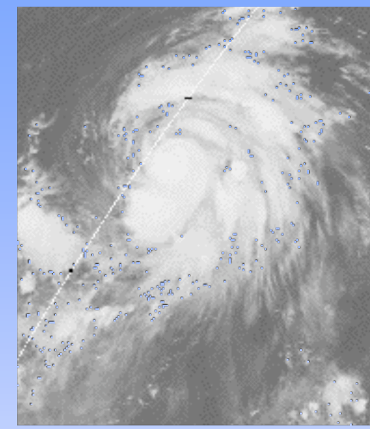


LAYOVER



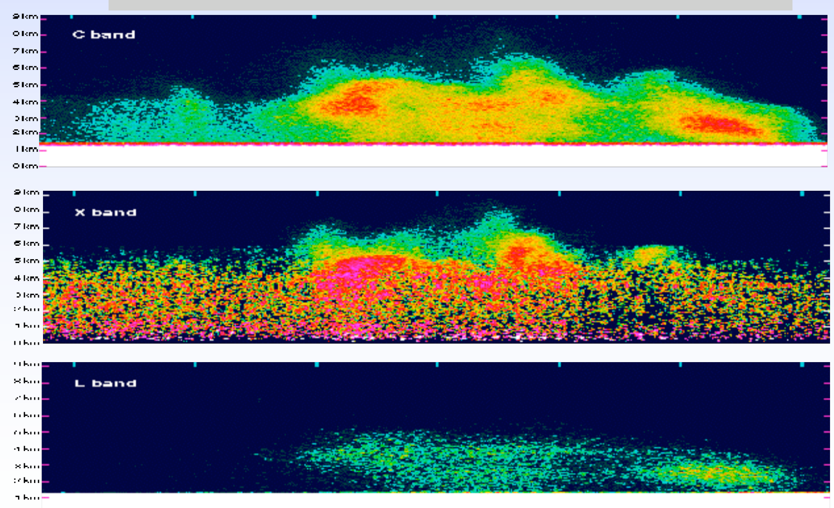
EVIDENCES FROM SIR-C SAR MISSION

- **SIR-C radar aboard the space shuttle Endeavour**
  - over the Western Pacific (orbit number 103), data take requests coincided with the passage of Endeavour over and **across Typhoon Seth on Oct. 6, 1994**
  - The SIR-C radar antenna beams were **perpendicular to the Earth** and data takes were executed with the correct radar operating parameters.
- **First radar images of rainfall from space radars!!!**
  - The 3 panels show vertical sections (through the atmosphere) of the radar reflectivities measured over a **convective cell** during the beginning of data take 103.0, **at C-, X- and L-bands (VV polarization).** The X-band signal shows some residual contamination by the echo from the surface

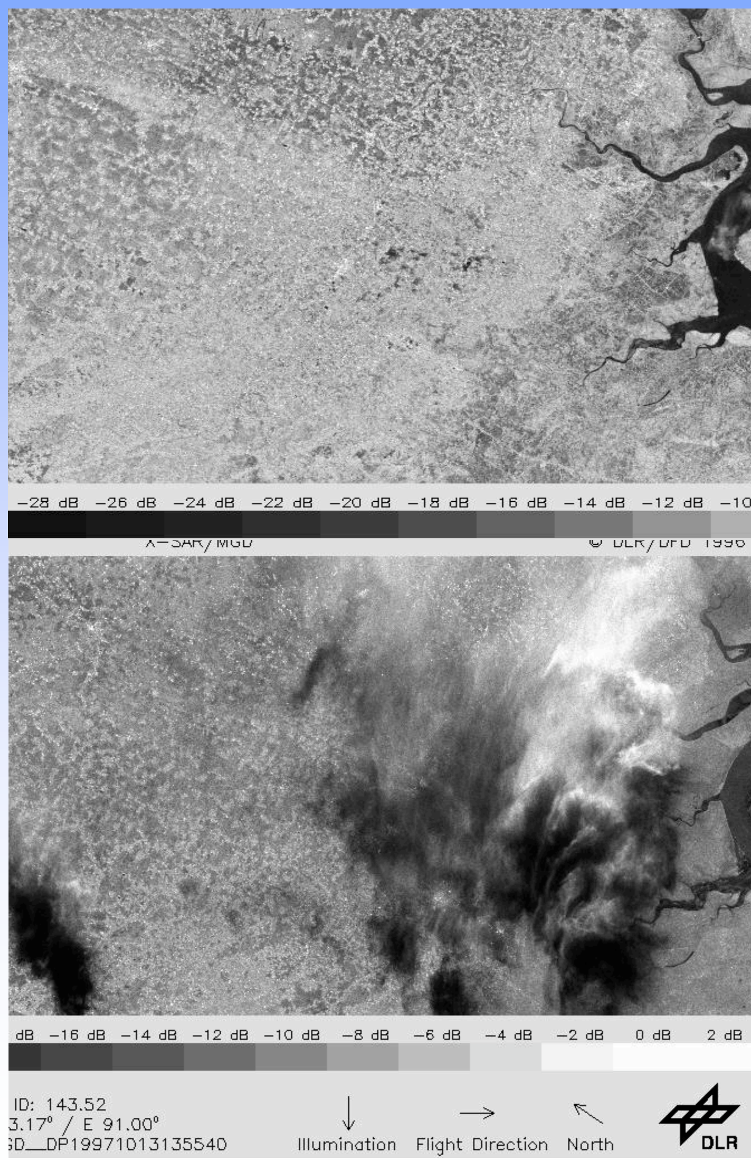


DT 103.0
(GMS IR, 6 Oct 94, 1732Z)

Jet Propulsion Laboratory
California Institute of Technology



CASE STUDY FROM X-SAR SIR-C MISSION



DLR X-SAR aboard Endeavor Shuttle Mission

- *Swath width: 100 km*
- *Resolution: 300 m*
- *Polarization: VV*

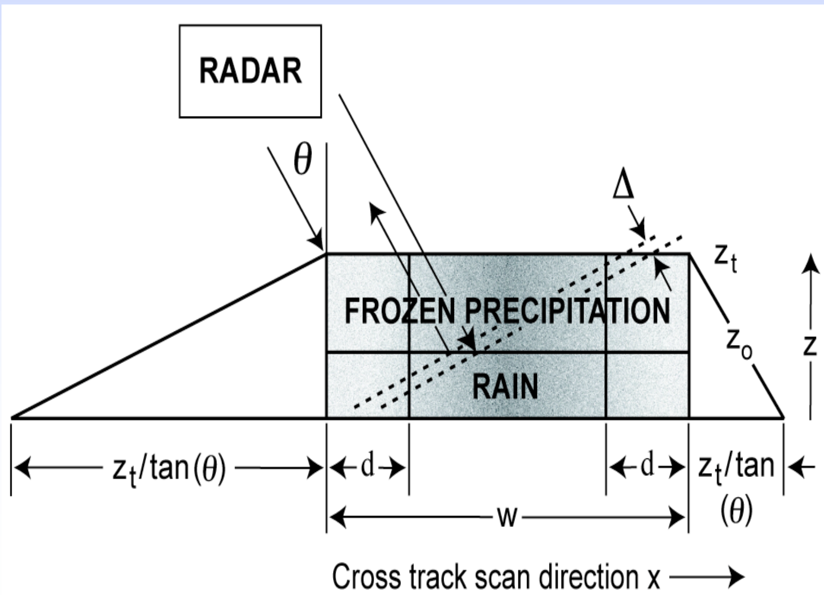
(Upper Panel) *View of Calcutta (22.8° N x 91.2° E) on 7 October, 1994.*
(Lower Panel) *Same scene on 18 April, 1994.*

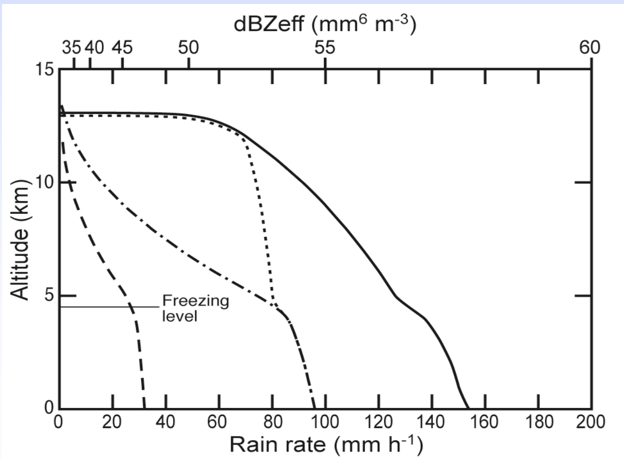
NOTES
*- **possible scattering by frozen hydrometeors** in the upper right, scattering and attenuation by rain in middle-lower right, and possible absorption by rain only in the lower left.*
*- the **maximum Normalized Radar Cross Section** (NRCS) of the scattered signal is ~ -3 dB and the minimum NRCS value in the shaded area is ~ -30 dB.*

MODELING SAR RESPONSE

- **Assumptions**
  - **Plane-wave incidence** (avoid spherical wave front corrections)
  - **Frozen atmosphere** (avoid Doppler broadening due to hydrometeors)
  - **2-D geometry** stratified along cross-track (x-z) view with **non-uniform profiles**
  - **Factorization** of the x (cross-track) and z (vertical) precipitation profile
  - **Liquid** (rain) and **ice** (graupel) hydrometeor **profiles**

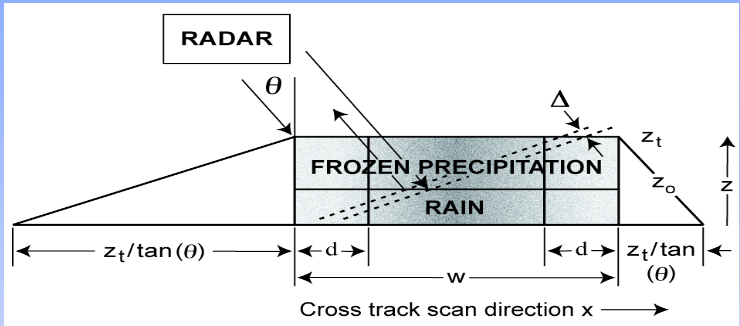
- **Objective**
  - Compute the **Normalized Radar Cross Section** (NCRS or σ_{SAR})





SAR RESPONSE DUE TO RAINFALL

- **Scattering mechanisms**
  - Surface back-scattering
  - Volume back-scattering
  - Slant geometry view
  - Attenuation (*k*) model at X band
  - Reflectivity (η) model at X band
  - Surface NCRS: - 7 dB



$$\sigma_{SAR}(x) = \sigma_{srf}(x) + \sigma_{vol}(x)$$

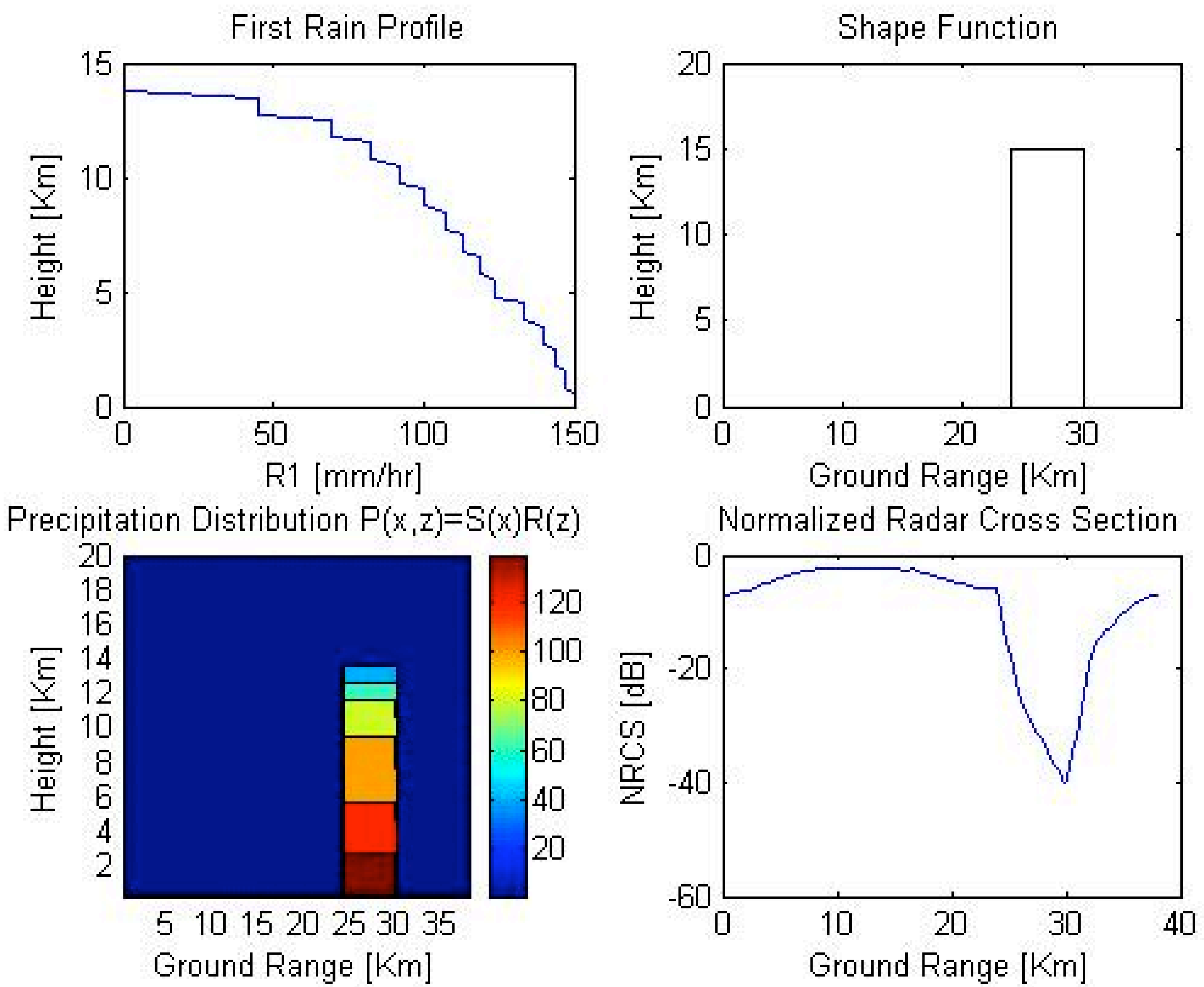
$$\sigma_{srf}(x) = \sigma^0(x) e^{-2\int_0^\infty k[x(z)]\frac{dz}{\sin\theta}}$$

Surface effects

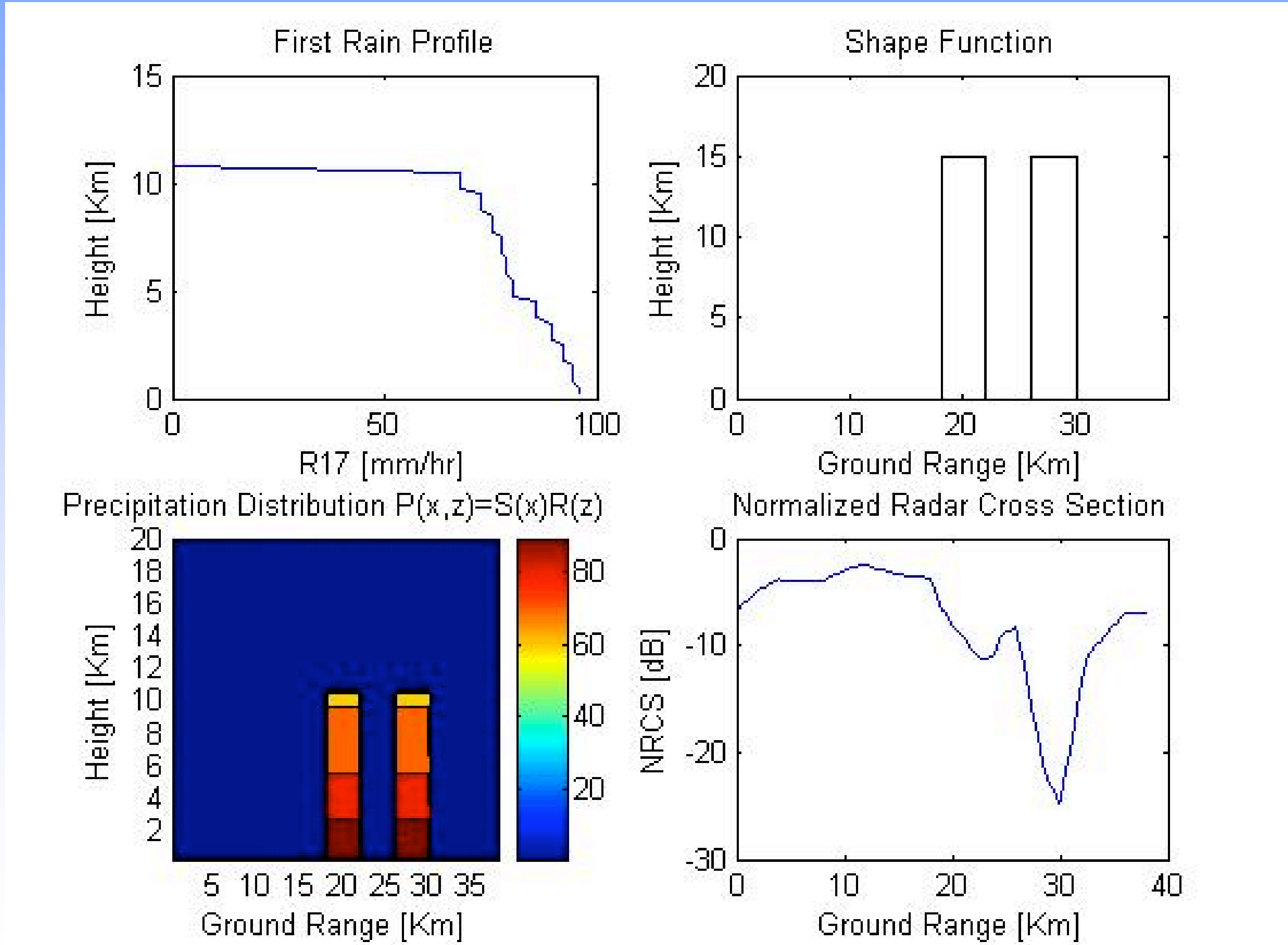
$$\sigma_{vol}(x) = \int_0^\infty \eta[x(z)] e^{-2\int_z^\infty k[x'(z')]\frac{dz'}{\sin\theta}} dz$$

Volume effects

EXAMPLES OF MODELED SAR RESPONSE

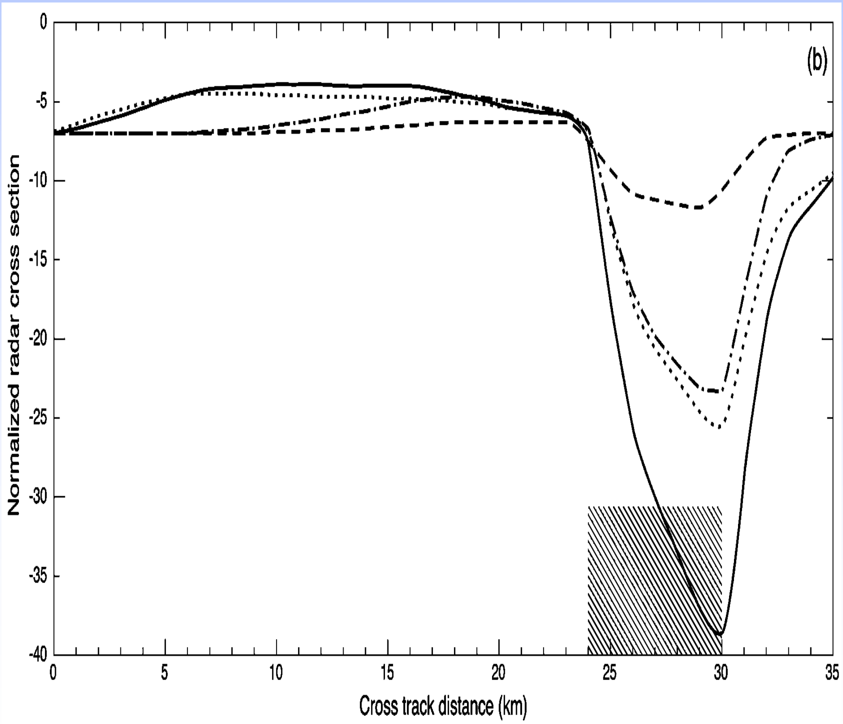


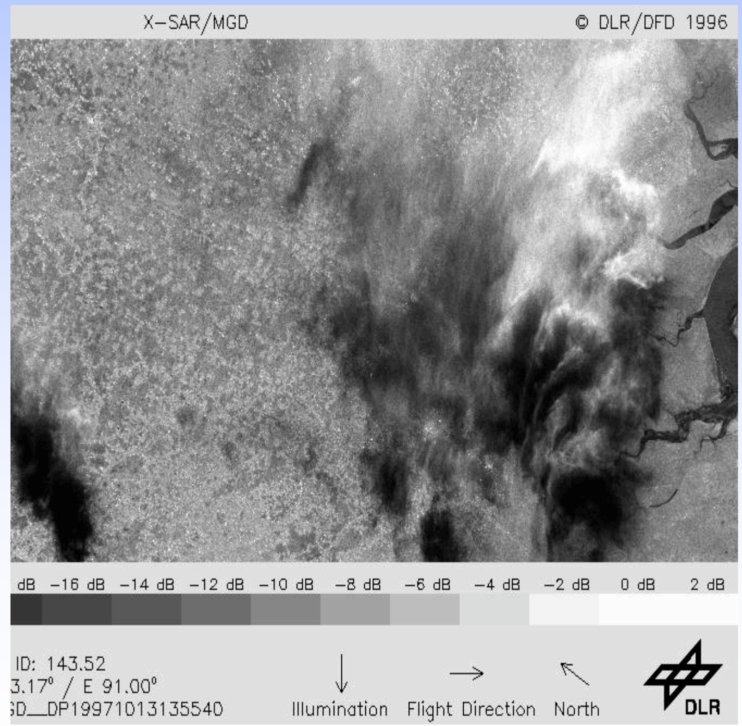
EXAMPLES OF MODELED SAR RESPONSE



FEATURES OF SAR RESPONSE TO RAIN

- **SAR response features**
  - Ice hydrometeors tend to enhance backscattering
  - Liquid hydrometeors tend to attenuate NCRS
  - Dependence on the precipitation horizontal-vertical shape
  - Slant view geometric effects





RAIN RETRIEVAL FROM SAR DATA

- **METHODOLOGY**
  - Recognize the precipitation spatial shape
  - Identify main features of SAR NCRS response
    - Zero-crossing NCRS nodes
    - Shape moments and stationarity points
  - Separate rain from ice hydrometeors
  - Exploit correlation along vertical precipitation profile V(z)

$$<V_{rain}(z)>=\frac{<V(z)>w}{\int_0^{\hat{w}} H(x)dx} \qquad V_{snow}(z)=\frac{<R(x,z)>}{\int_0^{w} H(x)dx}=V_{rain}(z_0)\left(\frac{z_t-z}{z_t-z_0}\right)^p$$

- **PROTOTYPE RETRIEVAL OF RAIN AND SNOW**

$$<\hat{V}_{rain}(0)>=23.30+1.13\int_{\hat{x}_0}^{\hat{x}_{max}}\left[dB\sigma^0(x_{max})-dB\sigma_{SAR}(x)\right]dx-21.62\int_0^{\hat{x}_0}\left[\sigma_{SAR}(x)-\sigma^0(0)\right]dx-2.58\hat{w}$$

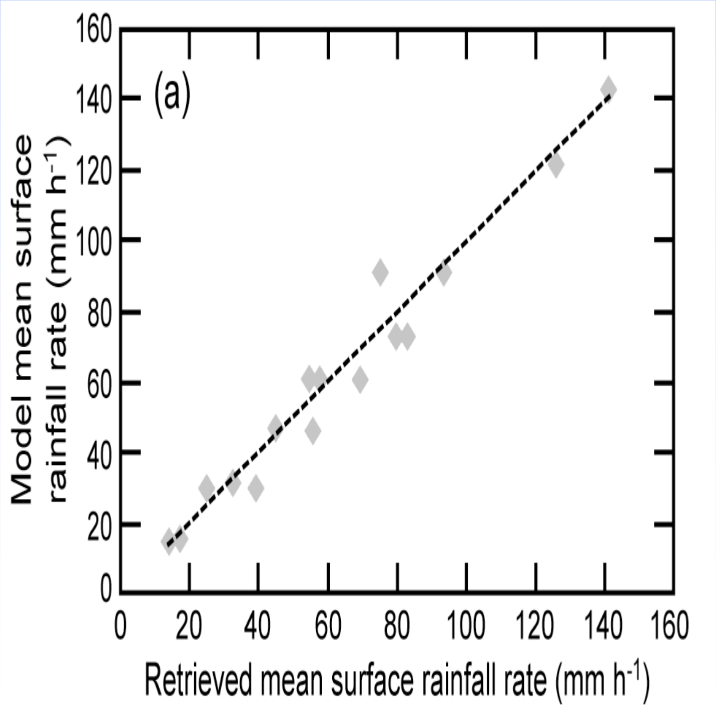
$$<\hat{V}_{snow}(z)>=\frac{183\left(\int_0^{x_0}[\sigma_{SAR}(x)-\sigma_{SAR}(0)]dx\right)^{0.94}}{\hat{w}^{1.04}}$$

STVDIVM VRBIS
LA SAPIENZA

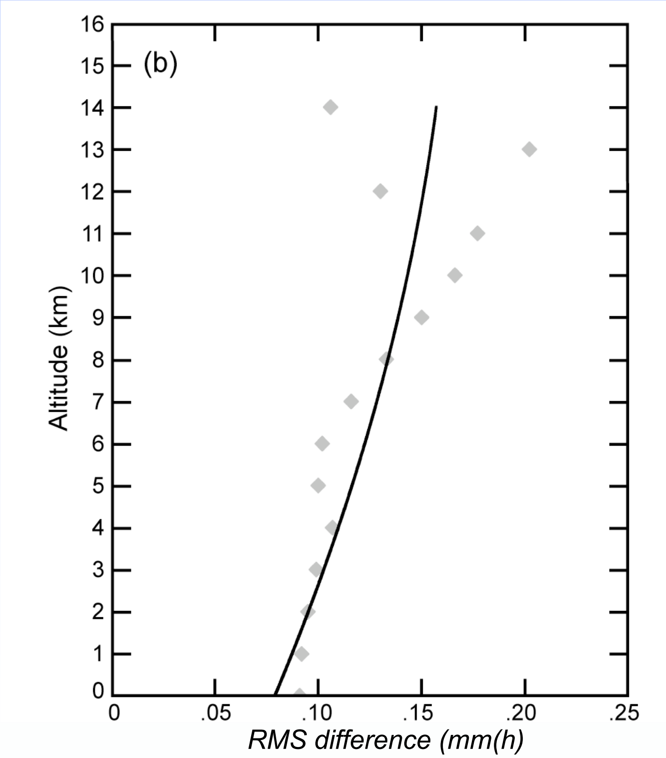
RAIN RETRIEVALS FROM SAR DATA

- **Simulated 2-D scenario**
  - Rectangular, triangular and double-column shapes
  - Modeled vertical profiles
  - No noise on NCRS response and surface NCRS

Surface mean rain-rate

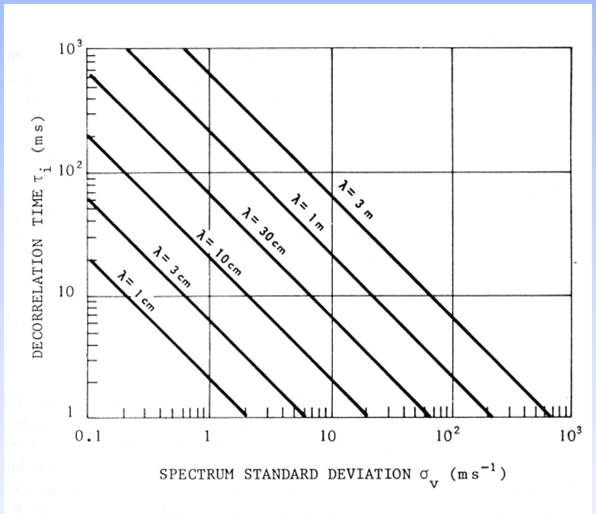


Mean precipitation profile



ISSUES ON X-SAR RAINFALL RETRIEVAL

- **Azimuth (along-track) resolution**
  - Nominally, $\Delta a = L/2$ for a fixed target
    - But, precipitation has an **inherent Doppler spectrum**



•*Snow:* $\sigma_v = 0.5\ m/s$
•*Rain:* $\sigma_v = 1\ m/s$

$$\sigma_{f_d} = (2/\lambda)\sigma_v$$

Doppler analysis of random target

$$\Delta a = \sigma_v (2R/U_{sat})$$

Cosmo Sky-Med ScanSAR

Nominal Δa: 30 m

Degraded by rain effect: ~300 m

- **Rain-rate estimation sensitivity**
  - Depending on Signal-to-Noise ratio and receiver noise $S/N \propto aR^b$
  - For standard relations at single-pulse X-SAR: $R_{\min} \approx 0.1\ mm/h$
    - *Improvements: incoherent integration of SAR pulses*
    - *Criticality: beam filling effects*

CONCLUSIONS

- **SAR are not nor microwave radiometers neither weather radars, but …**
  - **SAR response looks very similar to MW radiometers**
    - Dependence on precipitation **integrated effects**
    - **No range** resolution
    - Use of **slant view** as probing instead of multifrequency radiometers
  - **SAR retrieval techniques** have some in common with **Precipitation Radar**
    - **Surface backscattering** reference meyhods to evaluate Path Attenuation
    - **High spatial resolution** (even higher than current PR and DPR!)

RainSAR?!